Effect of the Discharge Voltage on the Performance of the Hall Thruster

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Abstract In this paper, a two-dimensional physical model is established according to the discharging process in the Hall thruster discharge channel using the particle-in-cell method. The influences of discharge voltage on the distributions of potential, ion radial flow, and discharge current are investigated in a fixed magnetic field configuration. It is found that, with the increase of discharge voltage, especially during 250-650 V, the ion radial flow and the collision frequency between ions and the wall are decreased, but the discharge current is increased. The electron temperature saturation is observed between 400-450 V and the maximal value decreases during this region. When the discharge voltage reaches 700 V, the potential distribution in the axis direction expands to the anode significantly, the ionization region becomes close to the anode, and the acceleration region grows longer. Besides, ion radial flow and the collision frequency between ions and the wall are also increased when the discharge voltage exceeds 650 V.

Keywords: Hall thruster, particle-in-cell, discharge voltage, discharge efficiency

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(Some figures may appear in colour only in the online journal)

1 Introduction

Hall thruster (shown in Fig. 1), a kind of small thrust device for spacecraft orbiting, shows outstanding performance on the efficiency (above 60%), specific impulse (in the order of $10^3$ s) and reliability. Therefore, it is widely applied to achieve the spacecraft promotion tasks such as attitude control, station keeping, orbital transfer and so on [1−3]. In recent years, with the continuous development of large satellite platform, micro-satellite network, deep space exploration and other space technologies, the high performances of the Hall thruster are also demanded, which promotes the development of its technology.

The Hall thruster has been experimentally and theoretically investigated by many researchers [4−7]. It has been believed that increasing the discharge voltage can effectively improve the specific impulse of the Hall thruster [8−10]. Meanwhile, since 1997, the United States, Russia and the European Space Agency have paid great attention to the high-voltage discharge problems of the Hall thruster and a large number of experimental studies have been performed [11−15]. The U.S. NASA-developed NASA-173M [12], the BHT Series Hall thrusters (BHT-1000, BHT-1500, BHT-8000) [13], the Russian-designed SPT Series Hall thrusters (SPT-100, SPT-115, SPT-140) [14] and the ESA-developed PPS Series Hall thrusters (PPS1350-G, PPSX000, PPS500) [15] have adopted high discharge voltages to enhance the thrust and specific impulse, where the maximal impulse has been increased to more than 4000 s.

Fig.1 Fundamental diagram of Hall thruster

Recently, in order to approach the actual situation, in the study of macro discharge performance of the Hall thruster at different voltages, the magnetic field is adjusted to some extent to match the discharge voltage. However, for the facilitation of theoretical study, the magnetic field matching has not been consid-
Duration in the study of the channel parameters for different voltages. Y. Raitses from USA Princeton Plasma Physics Laboratory discussed the distribution of potential and electron temperature under different discharge voltages, and observed the existence of the electron temperature saturation phenomenon in the channel [16–18]. It is reported that there is a threshold voltage, below which the maximal electron temperature increases with the growth of discharge voltage. However, when the discharge voltage exceeds the threshold, the maximal electron temperature does not increase significantly, which may even decrease; this phenomenon is called electron temperature saturation. Ji Linzhe et al. from the Harbin Institute of Technology studied the mechanism of the electron temperature saturation phenomenon [19–21]. The results showed that the drop of the electron temperature within a critical interval rises from the decrease of the joule heating, while the reducing of the electron density in the critical interval leads to the significant reduction of the collision flux of electrons at the wall as well as the reduction of electron temperature. At present, the mechanism of electron temperature variation at different discharge voltages has already been understood, but due to the uncertainty of the complex conductive mechanism in the Hall thruster discharge channel, and the non-Maxwellian distribution and anisotropy of electrons, the collision between plasmas and the wall becomes complicated. In order to achieve a complete understanding of the conductive mechanism in the Hall thruster discharge channel, it is necessary to deeply research the changes of the particle characteristics in the Hall thruster channel under different discharge voltages, and analyze the physical mechanism which induces these changes.

In this paper, a two-dimensional physical model aiming to describe the plasma motions in the discharge channel of the 1 kW/P70 Aton Hall thruster is established using the particle-in-cell (PIC) method. The influences of discharge voltages on the electric potential, electron temperature, ion velocity, collision frequency and discharge current are investigated. By modeling the variation of physical parameters inside the discharge channel, the effect of discharge voltages on the discharge characteristics of the Hall thruster is also analyzed.

2 Physical model and boundary conditions

In this paper, two-dimensional space (axial z and radial r) and three-dimensional velocity coordinates \((v_z, v_r, v_\theta)\) are established according to the axial symmetry structure of the Hall thruster. The design of the PIC computation region is based on the actual discharge channel size of a P70 Aton Hall thruster, the channel length and width of which are \(z = 30\) mm and \(r = 14\) mm, respectively. The simulation region and the magnetic field configuration are shown in Fig. 2. The magnetic field of the program is calculated by FEMM software. The steps of the space and time are taken as 0.05 mm and 0.1\(\omega_p^{-1}\), where \(\omega_p\) is the plasma frequency. The initial electron temperature is 18 eV and the plasma density is \(1 \times 10^{18}/m^3\).

![Image](Fig.2) Simulation region and the magnetic field configuration

The Hall thruster discharge channel is numerically simulated via the Maxwell equations:

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \\
\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0},
\]

where \(\mathbf{E}, \mathbf{B}, \mu_0, \varepsilon_0\) and \(\rho\) represent the electric field, the magnetic field, the vacuum permeability, the dielectric constant and the electric charge density, respectively. The Poisson equation can be obtained by the Maxwell equations:

\[
\nabla^2 \Phi = -\frac{\rho}{\varepsilon_0},
\]

where \(\Phi\) represents the potential.

In the column coordinate system, the 2D Poisson equation can be written as

\[
1 \frac{\partial \Phi}{\partial r} \left( \frac{\partial \Phi}{\partial r} \right) + \frac{\partial^2 \Phi}{\partial z^2} = -\frac{e}{\varepsilon_0} (n_i - n_e),
\]

where \(n_i\) and \(n_e\) are the ion and electron densities, \(e\) is the unit of charge.

The discharge channel is divided by identical mesh spaces along the axial direction \(z\) and the radial direction \(r\). By applying the central difference method, Eq. (4) can be written as

\[
\frac{\Phi_{i+1,j} - 2\Phi_{i,j} + \Phi_{i-1,j}}{(\Delta z)^2} + \frac{1}{(\Delta r)^2} \left( \frac{r_{i,j+1}}{r_{i,j}} \Phi_{i,j+1} + \frac{r_{i,j-1}}{r_{i,j}} \Phi_{i,j-1} \right) - 2\Phi_{i,j} + \frac{r_{i,j-1}}{r_{i,j}} \Phi_{i,j-1} = -\frac{e(n_i - n_e)}{\varepsilon_0},
\]

Then Eq. (5) can be simplified as

\[
\frac{(\Delta r)^2}{(\Delta z)^2} (\Phi_{i+1,j} + \Phi_{i-1,j} - 2 \left( 1 + \frac{(\Delta r)^2}{(\Delta z)^2} \right) \Phi_{i,j}) + \frac{r_{i,j+1}}{r_{i,j}} \Phi_{i,j+1} + \frac{r_{i,j-1}}{r_{i,j}} \Phi_{i,j-1} = -\frac{e(n_i - n_e)}{\varepsilon_0} (\Delta r)^2,
\]

\[
(\Delta r)^2 \left( \frac{r_{i,j+1}}{r_{i,j}} \Phi_{i,j+1} + \frac{r_{i,j-1}}{r_{i,j}} \Phi_{i,j-1} - \Phi_{i,j} \right) = -\frac{e(n_i - n_e)}{\varepsilon_0} (\Delta r)^2,
\]
2.1 Equations of particle motions in the Hall thruster

For a single particle, the equations of motion for a particle with mass $m$ and charge $q$ in the electric and the magnetic field $E$ and $B$ are expressed as

$$\frac{d}{dt}(mv) = q(E + v \times B),$$

(8)

$$\frac{d}{dt}x = mv,$$

(9)

where $v$ is the velocity vector, and $x$ is the position vector.

The Boris method is an explicit algorithm with a second order accuracy, which is generally used to solve the equations of particle motion. The velocity $v^{-\Delta t/2}$ is firstly changed to $v^{-}$ through halftime electric field acceleration. Then according to the $v^{-}$, $v^{+}$ is obtained by calculating the rotating of particles in the magnetic field. At last, the new velocity $v^{t+\Delta t/2}$ is derived after another halftime electric field acceleration. The specific formulas are

$$v^{-} = v^{-\Delta t/2} + \frac{e\Delta tE}{2m},$$

(10)

$$v' = v^{-} + v^{-} \times t',$$

(11)

$$v^{+} = v^{-} + v' \times \frac{2t'}{1 + t'^{2}},$$

(12)

$$v^{t+\Delta t/2} = v + \frac{e\Delta tE'}{2m},$$

(13)

where $t' = \frac{e\Delta tB'}{2m}$, superscript $t$ represents the corresponding time step.

2.2 Boundary conditions of insulated wall

The boron nitride (BN) ceramic is adopted as the insulating wall material for the Hall thruster. According to the secondary electron emission model proposed by Morozov [22], when an electron interacts with the wall, one of the following four events may occur for the electron. The electron is either absorbed by the wall, reflected elastically, knocks out one electron, or knocks out two electrons. The corresponding probabilities of those events are

$$W_0 (\varepsilon) = 0.5 \exp \left(-\frac{\varepsilon^2}{43.5}\right),$$

(14)

$$W_r (\varepsilon) = 0.5 \exp \left(-\frac{\varepsilon^2}{30^2}\right),$$

(15)

$$W_2 (\varepsilon) = 1 - \exp \left(-\frac{\varepsilon^2}{1279^2}\right),$$

(16)

$$W_1 (\varepsilon) = 1 - W_0 (\varepsilon) - W_r (\varepsilon) - W_2 (\varepsilon).$$

(17)

3 PIC simulation results in Hall thruster discharge channel

3.1 Effects of discharge voltage on the distribution of electric potential and ion density

Fig. 3 shows the spatial distribution of ion density and electric potential. Region I marked in Fig. 3 is the ionization zone where atoms are ionized, when the discharge process is stabilized, the electron density is found to be almost the same as the ion density. Region II is the acceleration zone where ions are accelerated to produce thrust. It indicates that with the increase of discharge voltage, especially during 250-650 V, the ionization zone moves to the anode slightly and the ionization mainly takes place near 10-20 mm of the axial discharge channel. The spatial distribution of electric potential changes little, but the potential drop is enhanced with the increasing of discharge voltage, which leads to the increase of ion energy obtained by the electric field. When the discharge voltage increases to 700 V, the distribution of potential expands towards the anode dramatically and the ionization zone is compressed to the
anode; the simulation result shows qualitative agreement with the experiment results \[^{20}\]. The acceleration zone becomes longer and the radial potential drop is increased caused by the decrease of the verticality between equipotential lines and the wall surface. The acceleration zone is the region where ions obtain energy from the electric field to produce thrust. Therefore, a longer acceleration zone means that ions have more time to stay in the channel and bigger collision probability with the wall surface. Meanwhile, with increasing discharge voltage, ions obtain more energy from the radial electric field, so the efficiency and performance of the Hall thruster will drop predictably.

3.2 The distribution of electron temperature at different discharge voltages

Electrons in the channel, which are accelerated by an electric field to ionize the atoms, come from the cathode in the exit plane. The electrons are restrained due to the strong magnetic field, parts of the electrons are applied to ionize the atoms and others are conducted to the anode to sustain the discharge current by near the wall conductive mechanism. Fig. 4 shows the effects of the discharge voltage on the distribution of electron temperature, which indicates that the electron energy obtained by the electric field is enhanced with the increasing of discharge voltage as well as the electron temperature. When the discharge voltage increases to 700 V, the distribution of electron temperature expands towards the anode, which is the same as the variation of the electric potential distribution. The statistics of the maximal electron temperature under different discharge voltages are shown in Fig. 5. The electron temperature saturation is observed at 400-450 V, which is similar to the experimental result of Ref. \[^{18}\] that indicates the decrease of the maximal electron temperature. The reason for the decrease is that the sheath \[^{23-25}\] existing at the boundary of wall surface turns space saturation \[^{15}\] when the incident electrons flux equals to the secondary electrons flux, which leads to the decrease of sheath potential drop. The interaction between electrons and the wall surface is increased, which leads to the loss of electron energy and finally the decrease of electron temperature.

3.3 The distribution of radial ion velocity at different discharge voltages

Fig. 6 shows the effects of discharge voltage on the distribution of radial ion velocity, which indicates that the high radial ion velocity region near the wall of the exit is reduced with the increase of discharge voltage (250-650 V). This means the decrease of ions energy loss and collision flux between ions and the wall surface. Meanwhile, ions focusing also becomes better. The reduction of ion energy loss indicates the increasing of efficiency and specific impulse of the Hall thruster. As the increasing of discharge voltage, ion energy obtained from the axial electric potential is enhanced, which decreases the time duration for ions in the discharge channel. However, the increment of the radial potential drop is small, which decreases the increment of ions radial velocity, and all these reasons lead to the decrease of ions radial velocity near the wall of the exit. When the discharge voltage increases to 700 V, the ionization zone is compressed to the anode and the acceleration zone becomes bigger. Meanwhile, the verticality between equipotential lines and the wall surface is decreased as the expansion of axial potential, which leads to the increase of the radial potential gradient, and the region of high radial ion velocity is increased. The radial ion velocity has a great influence on the collision frequency between ions and the wall surface, and the increasing of radial ion velocity will enhance the collision frequency. Fig. 7 shows the effect of discharge voltage on the collision frequency between ions and the wall surface, it shows that with the increasing of discharge voltage, the collision frequency is firstly reduced during 250-650 V, but bounds back when the discharge voltage exceeds 650 V. The variation tendency is the same as Fig. 6.
3.4 The variation of discharge current under different discharge voltages

The discharge current is an important parameter to reflect the macro-performance of the Hall thruster, and the discharge voltage has a great effect on it. Fig. 8 shows the variation of discharge current (namely $I_d$) with the discharge voltage, it indicates that the discharge current increases with the increasing of discharge voltage, which is consistent with the result of Ref. [26]. Generally, there are two reasons causing the increase of the discharge current, one of which is enhancement of the near wall conductive current and the other one is the increasing of energetic electrons.

The formula of the near wall conductive current can be expressed as

$$I_w = \frac{\overline{\sigma j_{ew}}}{\omega_c^2 m_e} E_z = \frac{\bar{\sigma} j_{ew} m_e n_e E_z}{B^2},$$

(18)

where $I_w$ is the near wall conductive current, $j_{ew}$ is the electron flux flowing to the surface of the wall (m$^2$·s$^{-1}$), $\omega_c$ is the cyclotron frequency of the electron, $\overline{\sigma}$ is the total emission coefficient of the secondary electron. As the increasing of discharge voltage, the collision frequency between electrons and the wall surface is increased, shown in Fig. 9, which means the increasing of electron flux flowing to the wall surface. Therefore, the near wall conductive current grows according to Eq. (18). Besides, the binding effect of the magnetic field on the electrons is weakened as the increasing of electron temperature, which is caused by the growth of discharge voltage. Therefore, the electrons in the channel have more chance to reach the anode and contribute to the discharge current.

4 Conclusion

A two-dimensional physical model is established according to the Hall thruster discharge channel using the PIC method. The influences of discharge voltage on the distribution of electrical potential, electron temperature, ion velocity and discharge current of the Hall thruster are investigated. The numerical results indicate that with the increasing of discharge voltage, especially during 250-650 V, the ionization mainly takes place near 10-20 mm of the axial discharge channel, the electric potential has not expanded severely and the collision frequency between ions and the wall surface is reduced. Meanwhile, the electron temperature saturation which is observed at 400-450 V leads to the decrease of the
maximal electron temperature. The potential distribution in the axial direction expands significantly when the discharge voltage increases to 700 V, the ionization zone moves close to the anode, and the radial ion velocity, the radial ion flow and the collision frequency between ions and the wall surface are increased. Therefore, in order to ensure the thruster works normally and efficiently, the discharge voltage should be maintained below 700 V. When the discharge voltage exceeds 700 V, the thruster wall surface will be corroded intensively, and the performance and service life of the Hall thruster will be reduced.

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